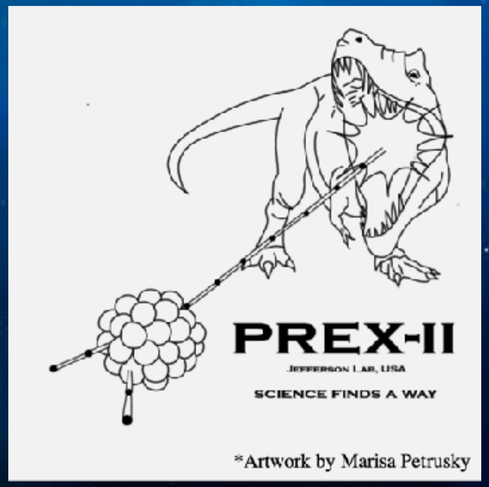
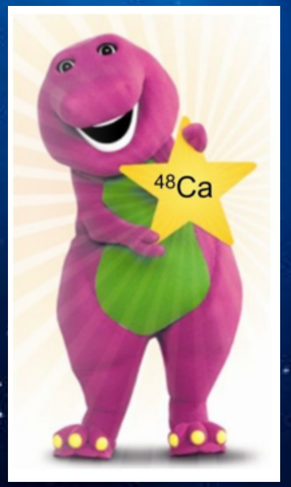
Parity violating electron and coherent neutrino scattering





Chuck Horowitz, Indiana U. Snowmass, Nov. 2021

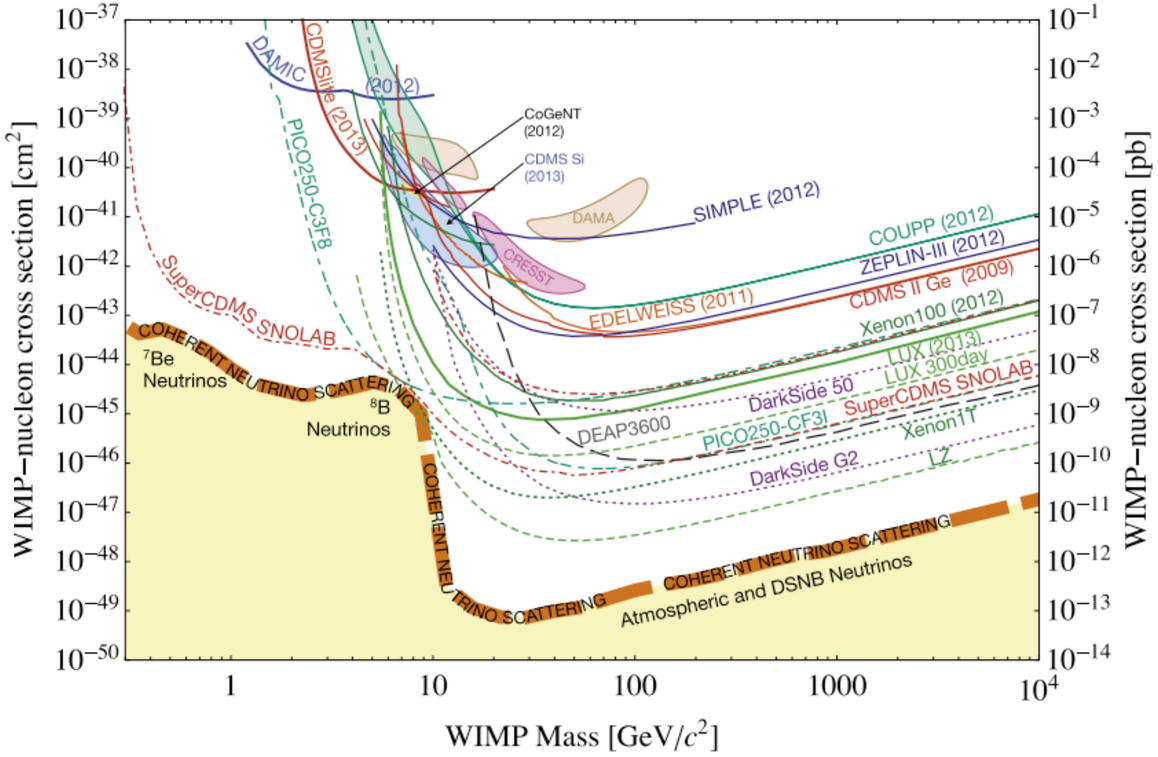
Parity violating electron scattering measures same coherent weak form factor $F_w(Q)$

$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T):
momentum transfer

weak nuclear charge

Form factor: F=1 ➔ full coherence



Coherent scattering provides neutrino floor for many dark matter searches

PV e scattering and nuclear theory (to extrapolate to neighboring nuclei) may be able to constrain weak from factors better than near future neutrino scattering exps.

This allows coherent neutrino scattering to probe non-standard neutrino interactions.

Present R_w measurements:
PREX(^{208}Pb) 1.3%
CREX(^{48}Ca) probed to 0.7%
Qweak(^{27}Al) 3.8%
Future:
MREX at Mainz ^{208}Pb to 0.5%

Parity Violation Isolates Neutrons

- In Standard Model Z^0 boson couples to the weak charge.
- Proton weak charge is small:

$$Q_W^p = 1 - 4\sin^2\Theta_W \approx 0.05$$

- Neutron weak charge is big:

$$Q_W^n = -1$$

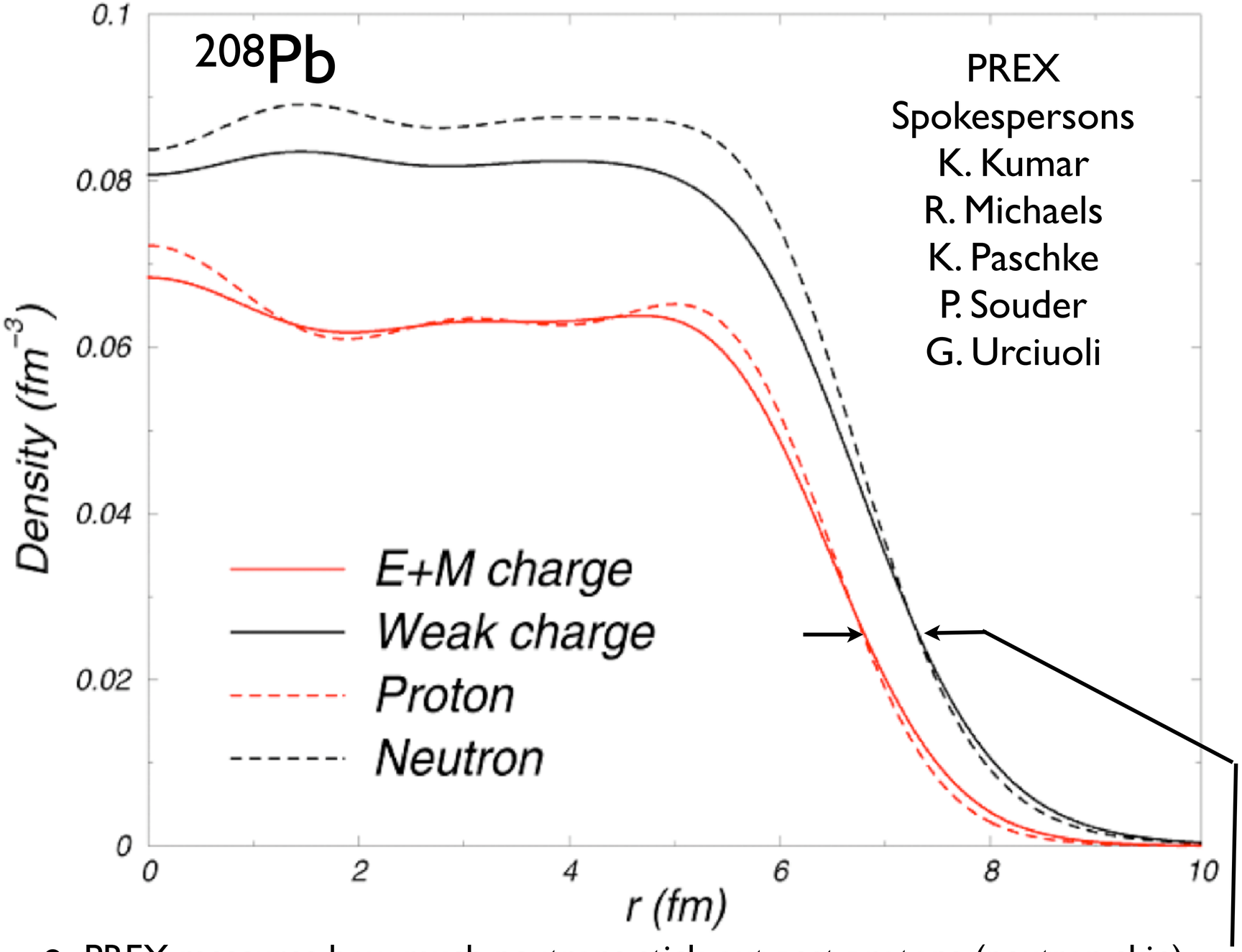
- Weak interactions, at low Q^2, probe neutrons.
- Parity violating asymmetry A_{pv} is cross section difference for positive and negative helicity electrons

$$A_{\mathrm{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{G_F Q^2 |Q_W|}{4\sqrt{2}\pi\alpha Z} \frac{F_W(Q^2)}{F_{\mathrm{ch}}(Q^2)}$$

- A_{pv} from interference of photon and Z^0 exchange.
- Determines weak form factor

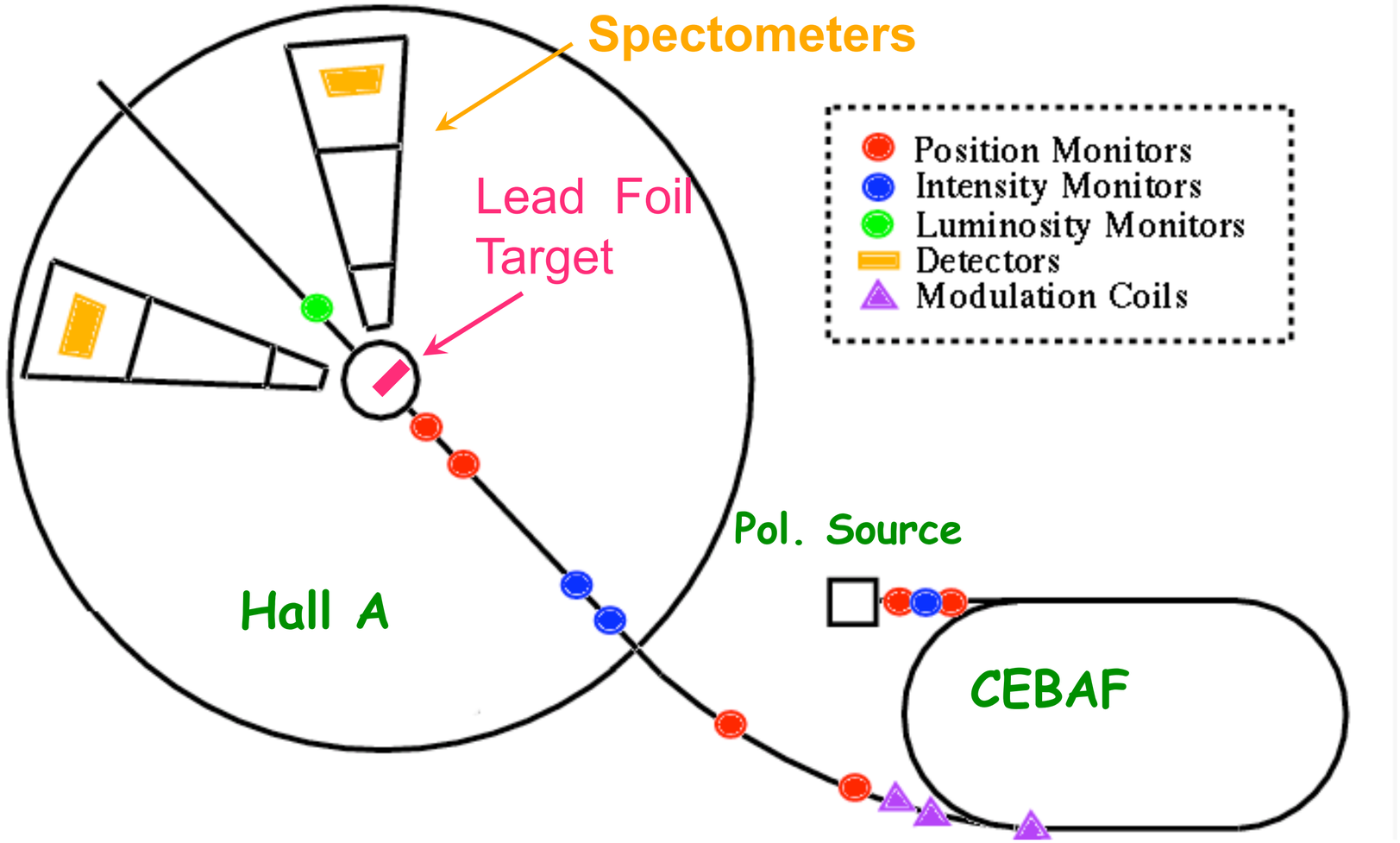
$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**



- PREX measures how much neutrons stick out past protons (neutron skin).

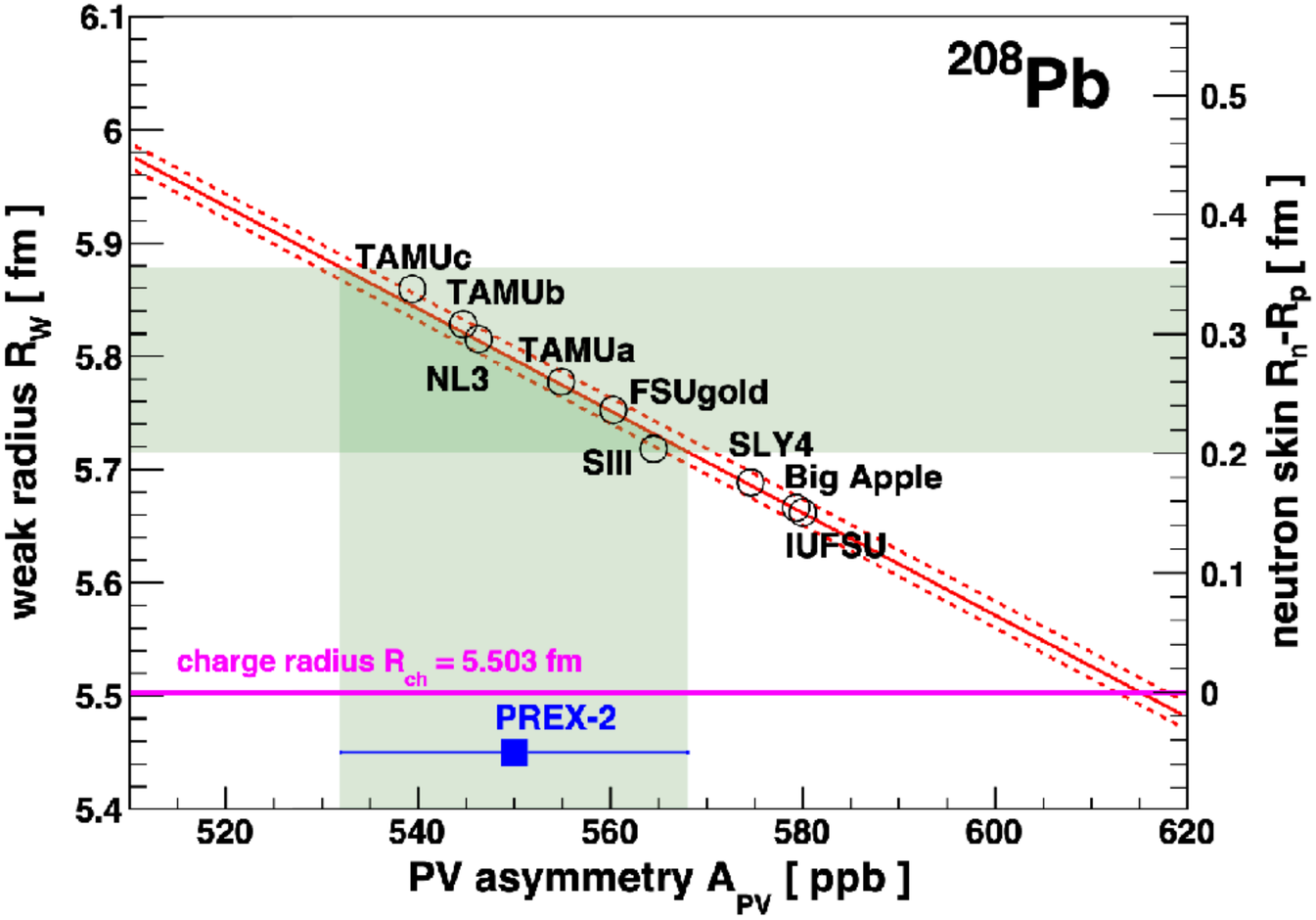
PREX in Hall A at JLab



R. Michaels

PREX-II

Parity violating asymmetry calculated including Coulomb distortions and integration over experimental acceptance



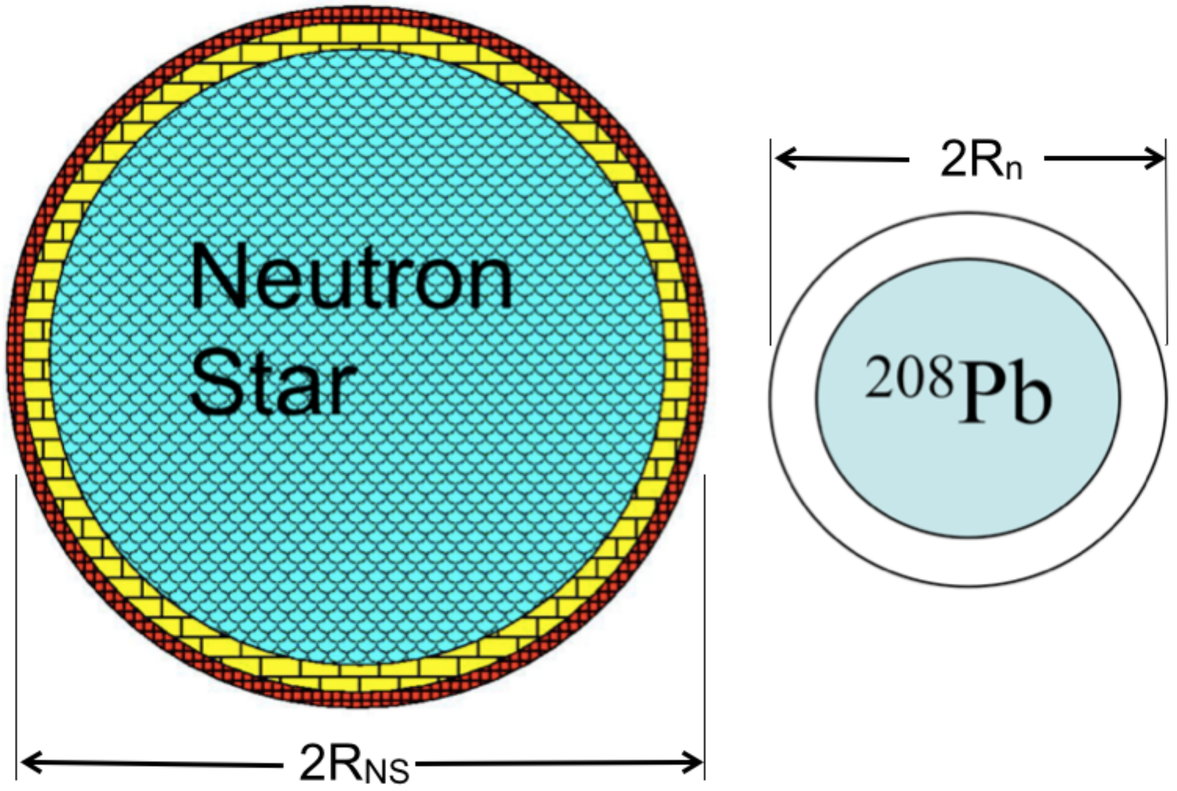
PREX-I+II Results

^{208}Pb Parameter	Value
Weak radius (R_W)	5.800 ± 0.075 fm
Interior weak density (ρ_W^0)	-0.0796 ± 0.0038 fm^{-3}
Interior baryon density (ρ_b^0)	0.1480 ± 0.0038 fm^{-3}
Neutron skin ($R_n - R_p$)	0.283 ± 0.071 fm

PREX-2 weak form factor:
$F_W(q=0.398\text{fm}^{-1})=0.3676+/-.0125$

Radii of ^{208}Pb and Neutron Stars

- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of neutron stars.



Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions, and equation of state.

Nuclear measurement vs Astronomical Observation

To probe equation of state

PREX, CREX measure neutron radius of ^{208}Pb and ^{48}Ca. Discuss systematic errors.

NICER measures NS radius from X-ray light curve. Some systematic errors.

Electric **dipole polarizability** from coulomb excitation. Potential systematic error from sum over excited states. Encourage ab initio calculations.

LIGO measured **gravitational deformability** (quadrupole polarizability) of NS from tidal excitation. Statistics limited but systematic errors controllable. Motivates third generation observatory such as Cosmic Explorer (40 km) or Einstein Telescope.

	Laboratory measurements on nuclei	Astronomical observations of neutron stars
Radius	PREX, CREX, COHERENT…	NICER
Polarizability	Electric dipole	Gravitational deformability

CREX ^{48}Ca

Extracting A_{PV}

Q^2=0.0297 GeV^2, Beam energy 2182.45 MeV

Blinded Corrected Asymmetry A_{corr}:
2080.3 ± 83.8ppb

$$A_{phys} = R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L(1 - \sum_i f_i)}$$

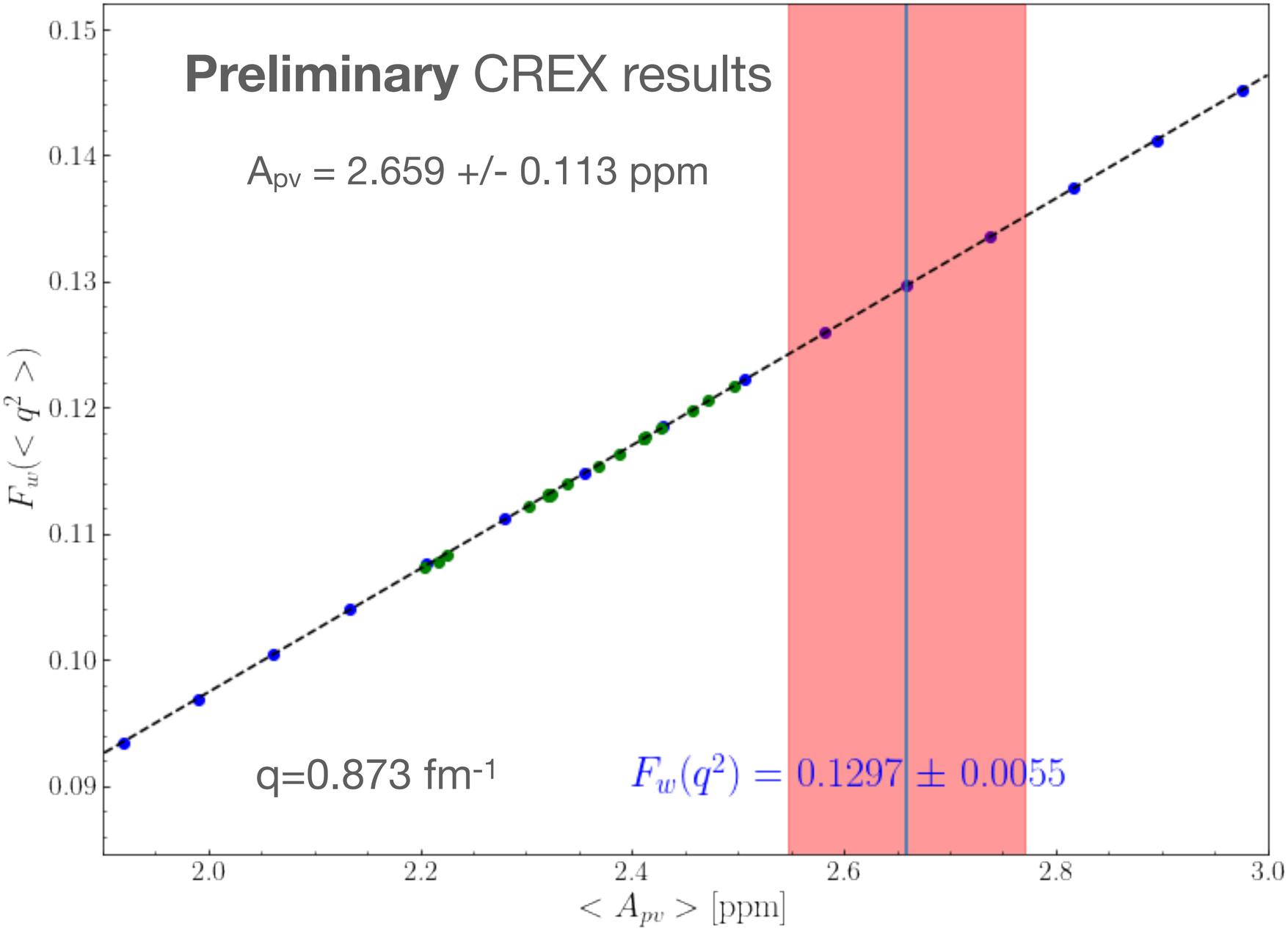
$$A_{corr} = A_{det} - A_{beam} - A_{trans} - A_{nonlin} - A_{blind}$$

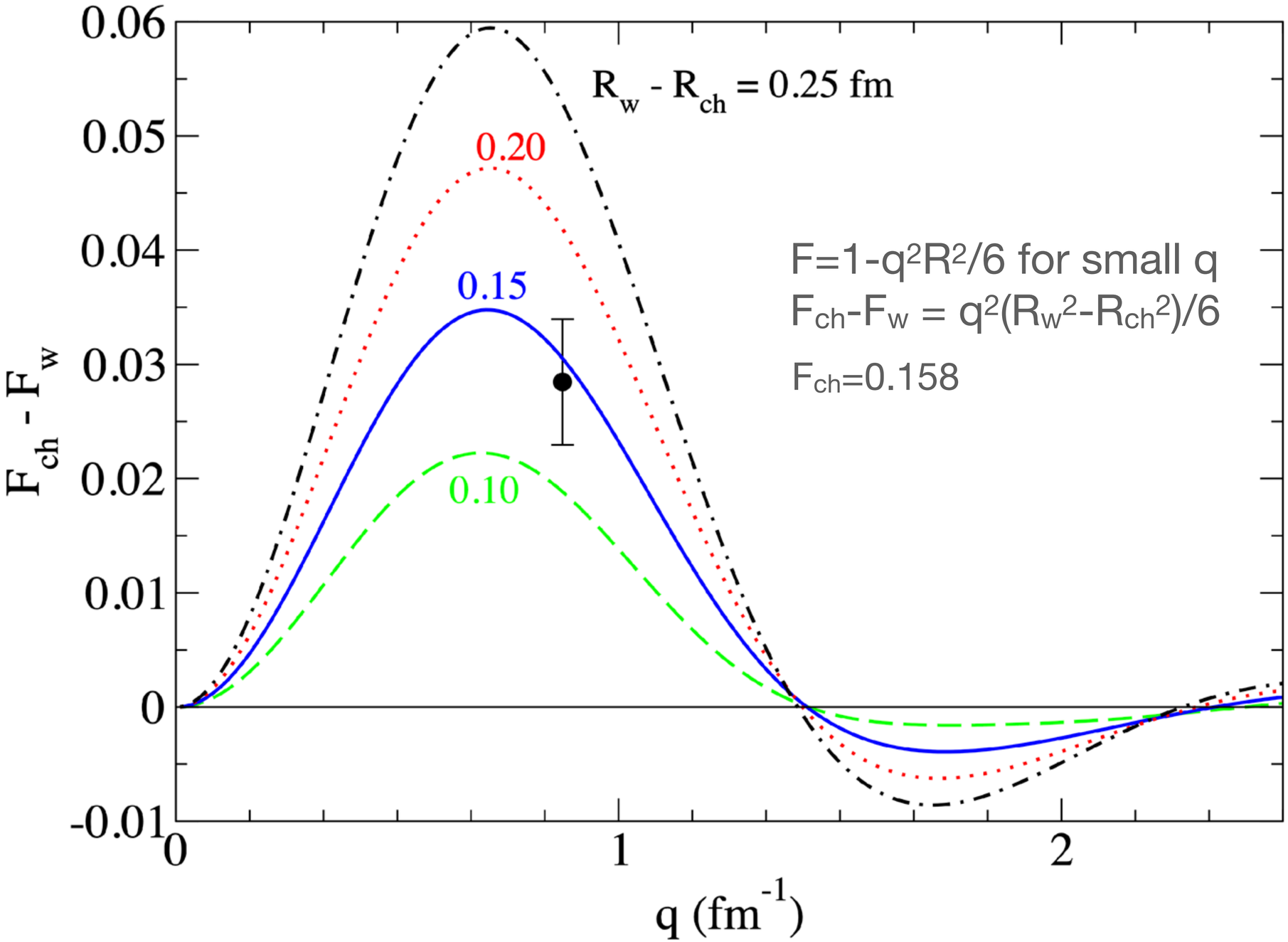
Blinded A_{PV}:
2334.8 ± 106.1(stat) ± 37.3(sys)ppb
[± 112.4ppb(tot)]

Unblinded A_{PV}:
2658.6 ± 113.2ppb (4.3%)

	A_{PV} uncertainty contribution [ppb]	A_{PV} uncertainty contribution [%]
Polarization	11.7	0.50%
Horizontal Polarization	12.7	0.54%
Vertical Polarization	0.9	0.04%
Acceptance normalization	21.0	0.90%
Beam correction	6.9	0.30%
Non-linear detector response	6.7	0.29%
Ca40 background	8.8	0.38%
Charge correction	1.1	0.05%
Inelastic contamination 2+	19.1	0.82%
Inelastic contamination 3-(1)	10.2	0.44%
Inelastic contamination 2-(3)	3.6	0.15%
Rescattering	0.4	0.02%
Total	**37.3**	**1.6%**

- When taken all into account the experimental systematic uncertainty comes to 1.6%, less than half the 4.5% statistical uncertainty
- Total uncertainty of is 112.4ppb (4.8%)


Preliminary CREX results
A_{pv} = 2.659 +/- 0.113 ppm
q=0.873 fm^{-1}
$F_w(q^2) = 0.1297 \pm 0.0055$
$F_w(< q^2 >)$
$< A_{pv} >$ [ppm]
0.15
0.14
0.13
0.12
0.11
0.10
0.09
2.0
2.2
2.4
2.6
2.8
3.0


0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
1
2
$F_{ch} - F_w$
q (fm^{-1})
$R_w - R_{ch} = 0.25$ fm
0.20
0.15
0.10
F=1-q²R²/6 for small q
$F_{ch}-F_w = q^2(R_w^2-R_{ch}^2)/6$
F_{ch}=0.158

CREX Physics Analysis

- From A_{PV} and acceptance determine weak form factor (Fourier transform of weak charge density) $F_W(q=0.873\ fm^{-1}) = 0.1297 +/- 0.0055$ This only assumes Coulomb distortions and radiative corrections included correctly. No model dependence.
- The weak radius R_w follows from F_W and modest assumptions about the surface thickness of the weak charge density. R_w will have an experimental error of about 0.025 fm (0.7%) and a **model error** of about 0.012 fm. (Stay tuned) Weak skin: R_w-R_{ch}
- The point neutron radius R_n follows from R_w and the **weak current operator** including significant spin-orbit currents. Neutron skin: R_n-R_p is different from weak skin because of spin-orbit currents.

Parity violation at Mainz

- At MESA (new high current low energy machine) measure:
  - –Weak charge of proton (improve on Qweak)
  - –Weak charge of ^{12}C (“Atomic PNC without the atomic structure”)
  - –MREX: Neutron skin thickness of ^{208}Pb (improve on PREX II by more than factor of two). Sensitive to R_w to 0.5%.
- R_w ^{48}Ca to 0.7% (CREX), ^{208}Pb (PREX-2 1.3%), (MREX 0.5%)
  - –Nuclear theory can extrapolate R_w-R_{ch} to R_w-R_{ch} in a neighboring nucleus, for example from ^{48}Ca (CREX) to ^{40}Ar.
- PREX/ CREX: K. Kumar, P. Souder, R. Michaels, K. Paschke, G. Urciuoli… Graduate student: Brendan Reed